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Scientific Justification for a Beam-Forming Array on the Green Bank Telescope

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14. ABSTRACT

National Radio Astronomy Observatory (NRAO) plans to build a beam-forming array for the Green Bank Telescope (GBT) capable of producing seven beams at L-band. The physical size of 21-cm feeds at the GBT makes it impossible to support a system with more than three beams if they are formed in the traditional fashion by stacking feed horns side by side. The beam-forming array is the most natural, efficient, and logical way to gain the advantage, and would represent a breakthrough in technology. Such an instrument would open up many new survey possibilities in spectral line and continuum imaging and polarization, as well as searches for new pulsars along the Galactic Plane. This document presents justifications and sample observing parameters for these surveys along with required system specification.

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Scientific Justification for a Beam-Forming Array on the Green Bank Telescope

1. Introduction

NRAO plans to build a beam-forming array for the Green Bank Telescope (GBT), capable of producing 7 beams at L-band. The physical size of 21-cm feeds at the GBT makes it impossible to support a system with more than three beams if they are formed in the traditional fashion – by stacking feed horns side by side. The beam-forming array is the most natural, efficient, and logical way to gain the advantage, and would represent a breakthrough in technology. Such an instrument would open up many new survey possibilities, in spectral line and continuum imaging and polarization, as well as searches for new pulsars along the Galactic Plane. This document presents justifications and sample observing parameters for these surveys, along with required system specifications. A table summarizing many of these requirements may be found at the end.

2. Technical Summary

The proposed beam-forming array would be based on the receiver designs summarized in Fisher & Bradley (2001a,b) , with a timescale to completion on the order of five years. The likely configuration of the system would be a prime-focus array of 38 sinuous elements, from which, through appropriate weighting schemes, 7 high-quality beams could be formed and spaced at arbitrary intervals on the sky. The beams may be formed in hardware or software, with the latter option being more flexible and therefore preferred.

The goal for system noise temperature is about 25K. Receiver gain and baseline stability should be as good as for a waveguide feed. Sidelobe levels and aperture efficiency will depend on the number of array elements used per beam. Near sidelobes may be better by a few dB and aperture efficiencies may be better by up to 10% compared to a single-mode waveguide feed, if the system uses more than the minimum number of elements per beam.

The receiver tuning range can in principle be roughly 30%, wide enough to cover the HI line at 1420 MHz through the OH line at 1720 MHz. The total bandwidth that can be correlated at one time will likely be smaller than this, as correlator costs scale roughly as the square of the number of elements per beam, and linearly with bandwidth and number of beams. Current estimates are that it will be realistic to do 100 MHz in software, though at least 200 MHz is strongly preferred fro pulsar searches. Related issues are whether to take polarization cross-products before or after beam-forming, and whether to Fourier-transform the signal from each element before forming the beams. This latter option would allow frequency-dependent weighting and would eliminate the need to pass data through the GBT spectrometer, but is efficient only when the total number of beams

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formed approaches the total number of elements. If Fourier transforms are not taken as part of the beam-forming algorithm, the proposed pulsar searches will require multiple copies of the planned spectrometer spigot card, or else a completely new backend, in order to handle the large data rates.

3. Galactic HI Emission Line Mapping

Galactic HI is seen in every direction in the sky at a peak line intensity of $\sim 0.5 - 125$ K. The lines usually have structure and are typically composed of several components with different velocities and different intensities. Broad, weak line wings are also found. Because 21 cm emission allows one to study the abundance, kinematics, and energetics of the atomic phase in every direction of the sky it is a unique tool for examining quite a number of phenomena, from magnetic fields and star formation to galactic rotation, the evolution of supernova remnants and the formation of the Galaxy.

The hydrogen 21-cm line and the continuum IR dust emission in the $100 \rightarrow 500$ μm region are the two ways to observe the diffuse interstellar gas. A complete sky survey of the 100 μm dust emission has been observed by the IRAS satellite with angular resolution $\sim 1'$ and excellent sensitivity (equivalent H column density $N(\mathrm{H})_{20} \sim 0.03$), where $N(\mathrm{H})_{20}$ is the H-atom column density in units of 10^{20} cm^{-2}. An HI survey that matched this angular resolution and had good sensitivity would provide the gas velocities needed to fully understand the IRAS survey.

Existing 21-cm line surveys have either good angular resolution or good sensitivity, but not both. Single dish surveys have good sensitivity but poor resolution: the best current survey with good sensitivity is the Leiden-Dwingeloo survey (LDS): angular resolution $36'$, sensitivity 0.07 K, equivalent to $N(\mathrm{H})_{20} \sim 0.005$ in a 3 km/s velocity range. There are two current array-based surveys, one in Australia (McClure-Griffiths *et al.* 2001) and one in Canada (Landecker *et al.* 2000). The Canadian survey has much better angular resolution $\sim 1'$ but a poor sensitivity of ~ 3.5 K. The GBT will provide sensitivity comparable to the LDS and an improvement in beam area by well over a factor of ten.

3.1. Science to be gained from a Galactic HI survey

- Stellar winds from such objects as O stars and evolved stars put energy into the interstellar medium and produce spherical shocks. HII regions have great overpressures; they produce large forces and should produce similar effects. They produce dense photodissociation regions (PDR's) where hydrogen is neutral and atomic, and adjacent regions where hydrogen is molecular (Hollenbach 1999). In both regions the densities are very large, making conditions ripe for self-induced star formation (Elmegreen & Lada 1977).

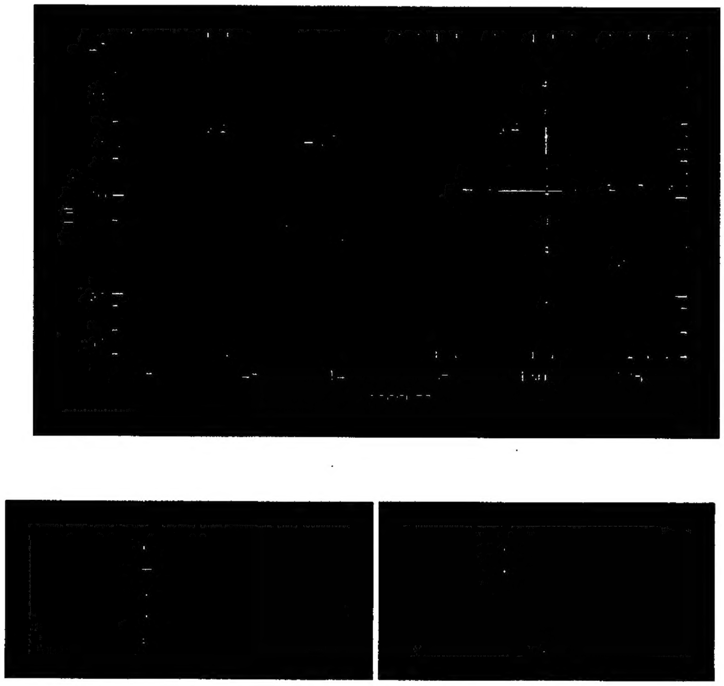

Fig. 1.— Top: Diffuse 100μm emission from IRAS, with $\sim 4'$ resolution. Increasing white corresponds to increased column density of interstellar matter. The numbers are the magnetic field strengths in μG measured with $36'$ resolution (Heiles 1989). Bottom: position-velocity images made along the two lines in the top panel. The vertical dotted lines correspond to $\pm 20 \mathrm{km\,s^{-1}}$.

- Supernovae and clusters of supernovae inject huge amounts of energy, producing not only huge spherical shocks but also associated structures such as mushroom-like features (English *et al.* 2000).

- Collisions between interstellar "clouds", and between an interstellar shock and a cloud, have been numerically modeled (Klein, McKee, & Colella 1994, Mac Low *et al.* 1994) but never recognized in observational data.

- Recent numerical models of ISM turbulence produce density/velocity cubes that can be directly compared with high-sensitivity, high-resolution 21-cm line data (Lazarian *et al.* 2001, Stanimirović & Lazarian 2001, Ballesteros-Paredes, Vázquez-Semadeni, & Scalo 1999, Stanimirović *et al.* 1999)

- The diffuse interstellar gas that surrounds molecular clouds should be undergoing forces associated with the clouds. There are a few observational studies of this atomic cloud-envelope

gas, but much remains to be done (Moriarty-Schieven, Andersson, & Wannier 1997, Wannier *et al.* 1993 and previous papers in that series).

- There appear to be regions in which the velocity gradients are very large with no apparent reason. These might well be regions where magnetic forces, possibly associated with magnetic reconnection, might be playing important roles. Finding such regions and measuring the associated magnetic fields would open an entirely new physical phenomenon in the interstellar medium. Figure 1 exhibits the HI structure in one of these regions. The top panel is from IRAS and has $\sim 4'$ resolution. There are no high-angular resolution HI data; the bottom frames show position-velocity images along the cross with $36'$ resolution, and these show that the velocity gradients reach the unusually large value $\gtrsim 10$ km s^{-1} deg^{-1}. A further example of this type of region is near the North Celestial Pole. It appears to be a small region undergoing spherical expansion, with filaments on the surface. The overall size of the region is about $20'$. The magnetic field strength in this region, as measured with a $36'$ beam, is very large, $\sim 10\,\mu$G. And in the general vicinity the field exhibits rapid structure with angle (Myers *et al.* 1995). Maps of the field with the angular resolution of the GBT would be exceedingly valuable.

- Kinematically and morphologically, the interstellar gas is dominated by huge spurts of energy from supernovae, stellar winds, and HII regions, which generate shocks. These produce sheetlike structures that can move rapidly. We have low-resolution studies of some objects; one, the North Polar Spur, is shown in Figure 2, which is a large-scale map of the North Polar Spur showing the spatial relationship between the HI, synchrotron, and X-ray emission. This structure is the most spectacular of its kind, but has never been studied over a significant fraction of its surface with better than ~ 30 arcmin resolution. The absence of better angular resolution prevents the delineation of the spatial relationships between the various components.

3.2. High-Velocity Clouds

High-velocity clouds (HVCs) are free-floating clouds of HI gas whose velocities do not fit with those expected from Galactic rotation. The origin of these clouds is not understood: they may be the leftovers from galaxy formation in the Local Group, the debris from satellite interaction with the Milky Way, or they may have been produced by a "Galactic fountain". It is also possible that a combination of these origins is correct, with the compact (about 1° in size), isolated high-velocity clouds (CHVCs) at large distances, and the larger complexes (tens of degrees across) currently interacting with the Milky Way. Figuring out the link between HVCs, compact HVCs, the Galaxy, and the Galaxy's satellites would be crucial to understanding their origin. At the resolution and sensitivity of the Parkes HIPASS survey, many new types of clouds and links were discovered. A survey with the sensitivity of the GBT would greatly enlarge the set of known HVCs and provide even more information about their connections to our Galaxy or to other galaxies in the Local Group.

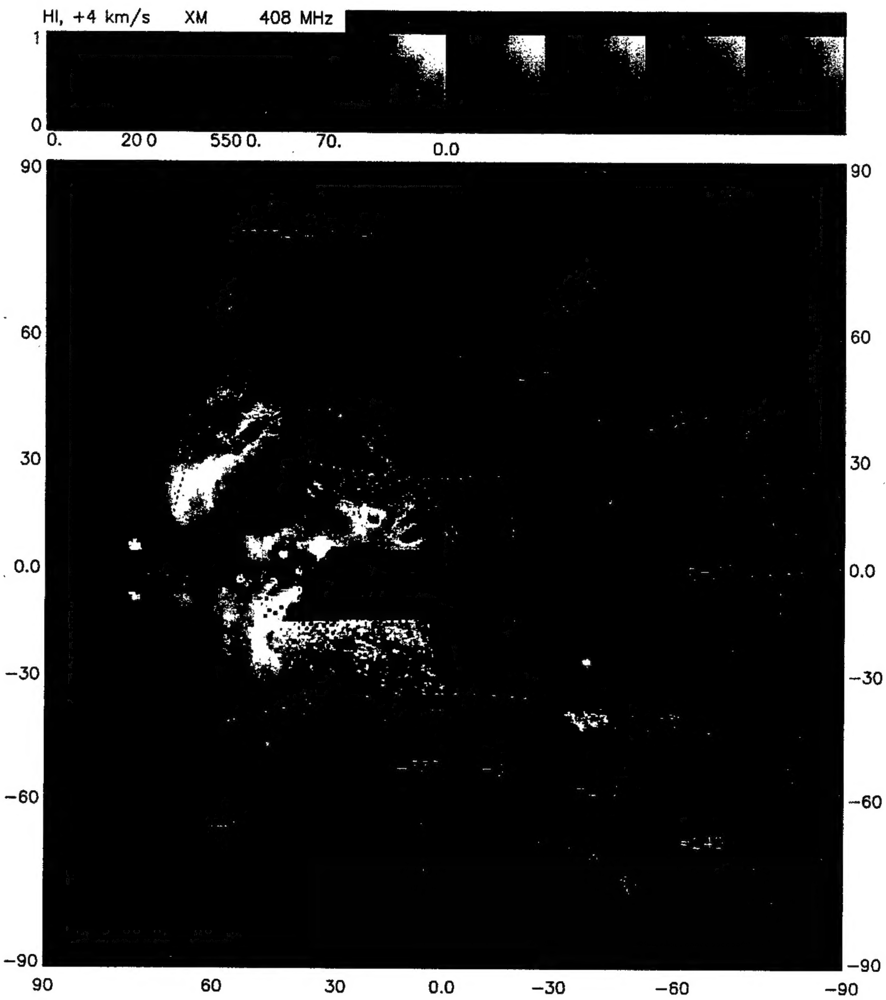

Fig. 2.— Large-scale map of the North Polar Spur showing the spatial relationship between the HI, synchrotron, and X-ray emission. Red shows HI at VLSR=+4 $\mathrm{km\,s^{-1}}$, most of which is swept up from inside the bubble; blue the diffuse synchrotron emission from relativistic electrons in the swept-up magnetic field; green the X-ray emission from the hot gas in the bubble's interior. These components are in order of decreasing radius–working out way from the outside of the onionskin inwards. The large blue swath in the middle contains no HI data. The outer components, the HI and the radio emission are sheetlike, in keeping with their production by the supernova shock.

3.3. Recommended Surveys with the GBT

The efficiency of the GBT for galactic HI observing is increased in direct proportion to the number of beams on the sky. With 7 beams, and sampling the HI sky with the GBT at the Nyquist spacing of $3.8'$ in each coordinate, it takes 36 pointings to cover a square degree. At an integration time of only 25 seconds per spectrum, which would be sufficient to get a peak S/N> 5 in all directions of the sky, a square degree requires 15 minutes of observation. To survey the northern sky above declination $-40°$ would take about 350 days at this rate. At high galactic latitude where the interesting work requires a S/N of many times larger than 5, or in directions where the interest is in a weak component or the line wings, longer integration times may be required.

An alternative project would be a survey of the Galactic Plane for $-10° < l < 260°$, $-10° < b < 10°$, or 5400 square degrees. This survey would take just under two months of observing time to complete and would exceed the latitude coverage and depth of the Canadian Galactic Plane Survey.

4. Polarization Mapping

4.1. Linear Polarization of Line and Continuum

Interstellar space contains distributed magnetic field and cosmic rays. The electron component interacts with the magnetic field to produce diffusely-distributed synchrotron radiation. The intensity of this radiation tends to change slowly with angle, which makes sense because the emitting regions are spread out over long lines of sight. This radiation is intrinsically highly polarized ($\sim 70\%$) perpendicular to the local magnetic field, but much of this gets washed out because of field randomness along the line of sight and, particularly at low frequencies, Faraday rotation. Faraday rotation is produced by the thermal electron component of interstellar gas together with the magnetic field, which rotate the plane of polarization of linearly polarized radiation by an angle that increases with λ^2.

The last ten years have seen the discovery of small scale structure in the polarization of this emission (e.g., Wieringa *et al.* 1993, Gray *et al.* 1999, Gaensler *et al.* 2001). The emission in any direction is emitted over long distances, making the existence of observable small-scale structure surprising. Faraday rotation is likely to be responsible. Thermal electrons occur in patches along the line of sight, and the effects on observed polarization depend sensitively on this distribution. Faraday rotation can also produce other effects, such as regions of sky with no polarization.

Gaensler et al. (2001) study these patches in a low-latitude region at 20 cm wavelength, and observe that the diffuse emission tends to be weakly polarized in "islands" having size ~ 10 to $20'$, separated by narrow "canals" of width a few arcminutes or less. The position angle of polarization of the patches changes by about 90° across the islands; the low polarization in the canals results from smearing of the rapidly-changing position angle by beam smearing. They consider whether the rapid angle changes can be caused by Faraday rotation, which would be a natural explanation

and is the one favored by previous investigators. On the contrary, however, they find no significant change in the Faraday Rotation Measure across these canals. This forces the conclusion that the emitting regions *themselves* are at least partly responsible for the canals. That is, the magnetic field suffers a sudden, significant change from one side of the canal to another. They believe that the distance to the particular emitting region studied is about 3 kpc, implying that the patch size is of order 10 pc.

This is an important and surprising phenomenon. First, the field remains roughly constant within a patch and then changes suddenly at the boundary to the adjacent patch. Second, for the polarization to be measurable at all the number of emitting patches along the line of sight cannot be too large, or else the polarization would wash out. Thus, the emitting region cannot extend too far along the line of sight, and yet the distance to the emitting region is likely about 3 kpc. One possible conclusion is that the Galactic diffuse synchrotron radiation is not so diffuse after all, but instead is produced in sheetlike regions with this field structure. The North Polar Spur, a nearby supernova-produced radio emitting shell, is sheetlike, and also exhibits sudden changes in the position angle direction (Spoelstra 1971). Figure 2 exhibits a multicomponent image of the North Polar Spur using the best available data; the current angular resolution limit of $\sim 36'$ is insufficient to delineate well the spatial relationships among the various components.

Further study of this and related polarization patterns is necessary to build up a statistical picture of the phenomenon. It will also be useful to extend the polarization measurements to the 21-cm line. The HI line has opacity, and careful measurements of the change in polarization caused by the line will tell whether the continuum polarization structures lie in front of or behind the HI. In the Galactic plane, the HI velocity is a good distance indicator, and one product of such an effort would be direct distance determinations of the continuum emitting regions.

Another goal would be to learn about the morphology of HI within these sheets, and particularly their relationship to the relativistic electrons that produce the synchrotron emission. The Galactic HI is generally also distributed in sheetlike structures. These likely trace powerful shocks in the interstellar gas that are produced by supernovae and clustered supernovae. If the synchrotron background is also produced by sheetlike structures, it seems quite probable that they are related. Indeed, the North Polar Spur exhibits the clear onionskin structure of the spherical shock, with the bright radio emission coming from a fairly thin spherical shell and the HI lying just outside in another spherical shell. This spatial relationship is clear because the shells are viewed tangentially. But if they were to be seen radially, across the thin dimension of the sheets, then the only observed structures would be those that occupy only a small fraction of the sightline. It seems quite possible that the magnetic field structure of the radio emitting region could be related to the structure of the HI shell. So if these shells were in close proximity, the HI might be seen sometimes in front, sometimes behind the radio emitting shell, and their relationship could be understood.

Gray et al. (1999) and Gaensler et al. (2001) see another type of structure in polarized continuum: fairly large self-contained regions having no polarization. Gaensler et al. explain one of these by a simple model of randomly aligned cells of magnetic field in a region of uniform electron

density $n_e \sim 20\ \mathrm{cm}^{-3}$ and $B \sim 5\ \mu$G with a random cell size ~ 0.2 pc. They infer that this region lies much closer than the synchrotron background that it depolarizes. Again, the 21-cm line absorbs this radiation, and by measuring the linear polarization of the line one may establish the relative distance of the depolarizing medium and the HI.

4.2. HI Emission Line Circular Polarization

The interstellar magnetic field produces observable Zeeman splitting of the 21-cm line. Measuring this splitting provides unique information on the interstellar field. The splitting depends only on the local field strength in the particular cloud and line-of-sight orientation. Along any particular sightline, the HI clouds are discernible and directly separable using the velocity peaks in the profile. Each peak can have a separately-derived magnetic field. Thus both the average field and its cloud-to-cloud fluctuations are observable. Moreover, the two components of HI (Warm and Cold Neutral Media, WNM and CNM) constitute most of the ISM mass and roughly half of the volume. The two components have markedly different properties and this likely extends to their magnetic properties.

Faraday rotation is the only other way to directly measure field strength; it is much easier to measure than HI Zeeman splitting, but more difficult to interpret. Faraday rotation occurs only in the Warm Ionized Medium (WIM) and, occasionally, HII regions. The WIM constitutes a minority of the ISM mass and probably a small fraction of the volume (see, e.g., Heiles 2001).

Measurements of HI Zeeman splitting can be done in absorption and emission. Splitting in absorption was detected long ago by Verschuur (1968) against Cas A. Until just recently, reliable measurements existed only towards two sources, Cas A and Tau A; other sources resulted in large upper limits. Heiles and Troland (2001, in prep.) are completing a very large survey of field strengths in absorption with the Arecibo telescope. They find that the typical field strengths measured in absorption are significantly weaker than those seen in HI emission. This is surprising, as the field should increase with volume density; absorption lines reveal cold HI, which has higher densities than the warm HI seen in emission lines; so absorption-measured field strengths should be larger than emission-measured ones.

Splitting in emission has been measured at hundreds of positions, primarily with the $36'$ beam of the Hat Creek 85-foot telescope (e.g. Heiles 1989). Most measurements are spot measurements, not maps, in long, narrow regions chosen because they resemble edge-on shocks or perhaps filaments. This almost certainly biases the regions observed to have higher-than-usual field strengths, which is probably an important reason for the abovementioned difference between field strengths measured in emission and absorption.

Emission measurements provide the invaluably important capability of mapping the field. Maps of Zeeman splitting should directly reveal structures of the type found by Gaensler *et al.* 2001, where the field changes suddenly in a small region. Moreover, combining Zeeman splitting with the linear

polarization measurements of either radio continuum or starlight provides the possibility of seeing the full three-dimensional field structure, in the way pioneered by Goodman and Heiles (1994) who used optical polarization for the linear polarization.

Maps of HI emission Zeeman splitting will contribute greatly to our understanding of the interstellar magnetic field. The required ten hours per position make a multibeam system a necessity.

4.3. Uniqueness of the GBT for Weak Diffuse Polarized Emission

The GBT is uniquely suitable for measurements of extended diffuse polarization because of its clear aperture. The Arecibo telescope is the other potential useful instrument. Heiles et al. (2001) have investigated the characteristics of Arecibo in detail and find that its ability to measure such emission is limited by instrumental effects caused by the central blockage. In contrast, the GBT has a clear aperture and will have no significant polarized sidelobes. The only significant effect at the GBT will be beam squint, predicted for the GBT to be about an arcsecond, which is easily corrected. The GBT will be the best telescope in the world for measuring Zeeman splitting of the 21-cm line in emission and should work in all cases—even for the two most difficult cases, the Galactic plane where velocity gradients are large and high-latitude broad lines from the Warm Neutral Medium.

5. Interstellar OH

5.1. OH and the Nature of the Atomic/Molecular Interface in Diffuse Clouds

A fundamental problem in astrophysics is the evolution of diffuse clouds to or from dense molecular clouds. This transition, chemically, dynamically, and morphologically, is poorly understood. The relation between HI, CO, and IRAS 100 μm emission is highly complex. The key missing species in these studies is OH, known to be the first molecule formed in gas phase after H_2 on grains. The problem is to map the large regions of suitable clouds such as the Polaris Flare cloud, in OH to understand the transition between truly diffuse clouds and CO ("dense" molecular clouds).

The North Polar Cap (NPC) is a region of diffuse atomic gas (Cutri & Latter 1994), containing HI but no CO. The correlation between HI intensity and 100 μm IRAS intensity is not 1:1, and a few regions are strongly "IR excessive" with 100 μm intensities greater than expected from the HI intensities and a standard dust/gas ratio. These regions may signal either HI gas which is very cold and optically thick, or, more likely, regions where HI has converted to H_2 but CO has not yet formed. The relation between the dust and HI is poorly understood: it is uncertain whether the dust accumulated in this region because the HI gas was denser there, or whether the dust arrived first, cooled the resident HI gas and thus caused an increase in density. Dust is essential for the

formation of molecules and controls the thermodynamics of the diffuse/translucent gas interface, but the initiation of these processes remain elusive.

The Polaris Flare region (Heithausen & Thaddeus 1990, Meyerdierks & Heithausen 1996; see Fig.3) is the next stage in the procession toward molecular clouds. CO is detected at low intensity over the region. The gas is 40% molecular by mass. The CO intensities in the Polaris Flare show more organized structure (representing peaks in density and/or column density) than do the HI or IRAS intensities in the NPC region. The CO peaks have negligible self-gravity, but these clumps may represent increasing immunity from the chaotic pressure field of the ambient (warmer) ISM. The densest CO region in the Polaris Flare has an extinction of only 1 magn, and the mean extinction of 0.3 magn corresponds to a volume density of $\sim 50\,\mathrm{cm}^{-3}$. Minor parts of this region are IR excessive, but the fraction of the Polaris Flare showing IR excess appears comparable to that of the more diffuse NPC cloud. Difficulties in disentangling these properties are expected, given the extreme dependency of the conditions marking the transition from atomic to molecular gas upon n, N, the UV radiation intensity, and the extinction.

Meyerdierks & Heithausen (1996) have made a detailed comparison of maps of HI, CO, and $100\,\mu$m IRAS in the Polaris Flare to try to disentangle the complexities. They find that the $100\,\mu$m emission per H atom is constant outside, but lower inside the CO emitting peaks (an IR "deficit"). They also find IR excess regions and reaffirm the conclusion that there is a third gas component of diffuse H_2, whose column density is in places comparable to that of HI. These H_2 peaks in general do not correspond to the CO peaks, either because CO is not collisionally excited, or because the H_2 is not effective in shielding the CO from photodissociation. Finally, they find a conversion factor X between CO line integral and $N(H_2)$ similar to that found for other cirrus clouds, but lower than values for galactic plane clouds derived from gamma ray studies.

To understand the intricate relations between HI, H_2, CO, and $100\,\mu$m emission, the diffuse chemistry of such regions must be taken into account. H_2 is a prerequisite to all other molecular species, and is formed on grains. The very first species formed in the gas phase is OH, which, with HCO^+, is a precursor of CO in diffuse cloud chemistry (van Dishoeck & Black 1986, Turner 1993. The details of the formation processes are such that OH "turns on" at extinctions lower than CO (van Dishoeck & Black 1986), in which range it is the most abundant molecular species. Further, the Einstein A coefficients of the 18 cm lines of OH are much smaller ($7 \times 10^{-11}\,\mathrm{s}^{-1}$; Turner 1966) than that of the CO 1-0 transition ($7 \times 10^{-8}\,\mathrm{s}^{-1}$). Thus we may expect to detect OH but not CO in the extinction range $0.2 - 0.5$ magn.

To understand the relations between the $100\,\mu$m emission and the atomic and molecular gas components at the diffuse-translucent transition region, we must account for all these important constituents. HCO^+ is rapidly destroyed by electrons to form CO, and has negligible abundance in the $0.2 - 0.5$ magn region. HII is of course not directly detectable, a limiting factor in understanding the IR excess and deficit phenomena. OH is a very close tracer of H_2 at extinctions where we expect H_2 itself to have just started to form on grains. By detecting OH at lower extinctions than

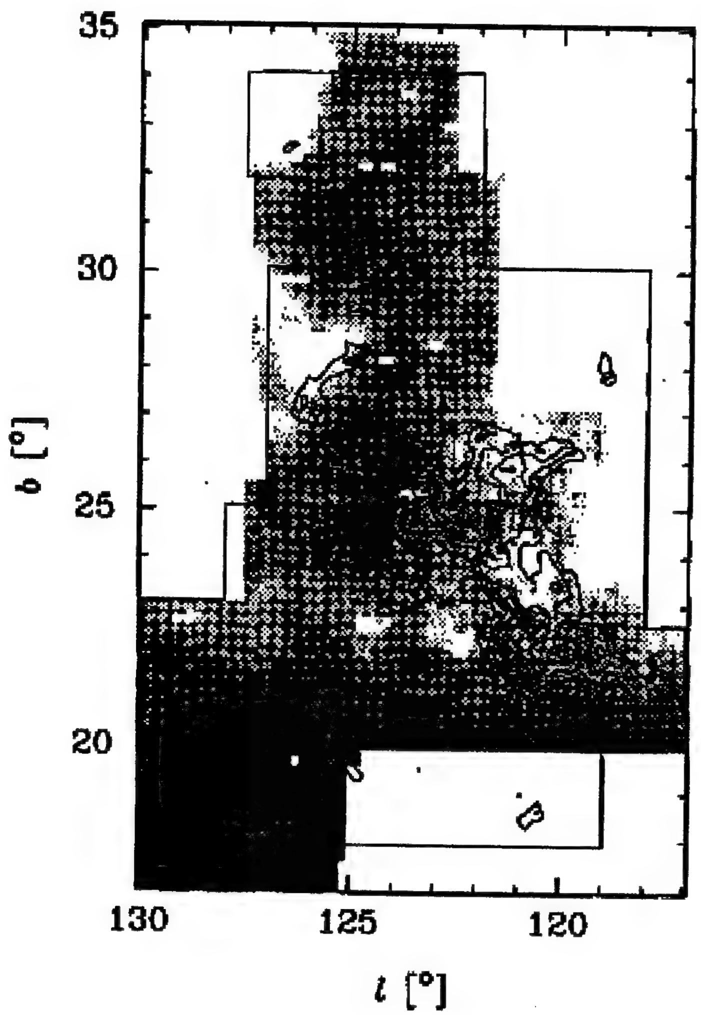

Fig. 3.— The Polaris Flare region. The grayscale represents the line integral of neutral hydrogen at low velocity ($-50.3\,\mathrm{km\,s^{-1}} \ldots +30.3\,\mathrm{km\,s^{-1}}$). White corresponds to $250\,\mathrm{K\,km\,s^{-1}}$ or less; the darkest shade to $750\,\mathrm{K\,km\,s^{-1}}$ or more. The overlaid contours are the map of the CO line integral, with contour values 2, 4, 6, … $12\,\mathrm{K\,km\,s^{-1}}$. From Meyerdierks & Heithausen (1996).

is possible with CO, and comparing its abundance with the IR excess and deficit regions, the goal is to understand the onset of molecules in diffuse gas more exactly than is possible using CO.

5.2. Anomalous 1720 MHz OH as a Tracer of Spiral Arms

As one result of the large-scale survey of the Milky Way in all four lines of OH (Turner 1979), 95 clouds were seen in the 1720 MHz line that were not apparent in the other three lines. 53 of these clouds were notable in their large extent, and in that their shapes were often long and narrow as projected on the sky. Velocities range up to tangential, implying very large linear sizes for some of them. Their estimated sizes are those of GMCs. The other 42 clouds were observed in only one position. The distribution of all 95 clouds appears confined to two inner spiral arms. Turner (1981,1982) argued that such clouds are in fact a new tracer of spiral arms. An (l,v) diagram of the 95 clouds resembles a similar diagram for HII regions (Lockman 1979, Downes *et al.* 1980), with a much smaller dispersion in the velocities than is the case for CO or H_2CO. Certainly the latter species show no clearly defined (l,v) structures which can be associated with spiral arms. By contrast, the 1720 MHz clouds, like the HII regions, show a run of points from $v = 0$ to 100 km/s and $-5° < l < 32°$ which correspond to an inner Scutum arm, and a run of points from 0 to 60 km/s and $10° < l < 50°$ which marks the Sagittarius arm.

The linewidths (1–3 km/s) of the 1720 MHz line are unusually small for OH lines in the general galactic plane, and the velocities are remarkably constant over the large extent of each cloud. The majority of the clouds exhibit main-line absorption or no detectable main-line emission to a level at least 3 times less than the 1720 MHz brightness, thus making the relative 1720 MHz anomaly stronger than found in any other region that is non-masering. 1720 MHz brightnesses are highly uniform over each cloud. VLA observations of four of the clouds detected no flux at 1720 MHz to a level consistent with uniform brightness over a region no smaller than 4′. The 1612 MHz line is always seen in absorption, usually stronger than the main lines. All of these attributes are consistent with a pumping model involving collisional excitation of the $\pi_{3/2}$ $J = 5/2$ rotational level at low temperatures (Guibert, Rieu, & Elitzur 1978). Such excitation, applied ONLY to this state, will enhance $T_{ex}(1720)$ but not the other 18 cm transitions, so long as the radiative decay at 120 μm to the ground state is optically thick (N(OH) $\gtrsim 5 \times 10^{14}$ cm^{-2}). Suitable values occur for 15 K $\leq T_k \leq$ 40 K and modest densities of 200 – 600 cm^{-3}. For $T_k <$ 15 K the $J = 5/2$ state will not be excited, while for $T_k >$ 50 K the IR radiation at 84 μm from dust grains will begin to excite the $\pi_{1/2}$ $J = 1/2$ state, and when this state decays radiatively it cancels the 1720 enhancement and favors a 1612 MHz excitation. The latter is never seen in these low-density clouds. It is clear that the 1720 MHz "anomaly" has much to say about the physical conditions in these clouds, for which no other tool seems to exist.

5.3. General Surveys of the Milky Way in OH

Turner's 1979 survey covered the entire available plane north of Dec. $-47°$ (with the 140′ telescope), within $|b| < 2°$. In unpublished data obtained in 1983 during the commissioning phase of the then new 18cm Rx/dual hybrid mode feed system, the same 1720/1612 anomaly was seen in many places between $2° < b < 5°$, and in addition a few cases were seen where the satellite line behavior was reversed. In all cases, the main lines were usually absent or at most much weaker than the satellite lines. There is much to be learned by a more extensive survey. Additionally, the 1979 survey found several clouds in the anticenter region of the Milky Way that exhibited weak OH (main lines) and no CO. A more extensive survey of this region with better coverage can be expected to turn up more such clouds which represent the transition between diffuse and dense molecular clouds.

6. Surveys for Distant Galaxies in HI

6.1. Background

Large-scale HI surveys for galaxies trace the evolution of the neutral gas in the universe with both redshift and environment. Optical redshift surveys are biased in regions which are obscured by the dust in our own Galaxy and the location of the stars in the local universe does not necessarily trace the location of the gas. Though numerous pointed extragalactic HI surveys have been completed, large scale blind extragalactic HI surveys are still in their infancy. In general, the blind surveys have been hampered by the speed with which they could cover a large region of the sky with decent sensitivity. This lack of speed and sensitivity has restricted the studies to small numbers of galaxies in small volumes of the local universe. This situation has just begun to change with the recent development of multibeam systems. Figure 4 shows the volume of space covered as a function of HI mass for the previous surveys. The sample sizes are still small for most surveys: e.g. 66 galaxies for AHISS (Zwaan *et al.* 1997), 75 for AS (Spitzak & Schneider 1998), and 265 for ADBS (Rosenberg & Schneider 2000). The volume of sky covered greatly increases when using a multibeam system (i.e. HIPASS and Parkes ZoA), and a large number of previously unidentified HI sources have been identified with these surveys. However, the resolution of HIPASS is only 15.5′, which leads to some confusion problems, and we are still restricted to HI masses above $10^7\,M_\odot$. It is with the combination of larger telescopes and more sensitive multibeam systems that we can assemble information about the gas in the local universe and, for the first time, at cosmologically important distances.

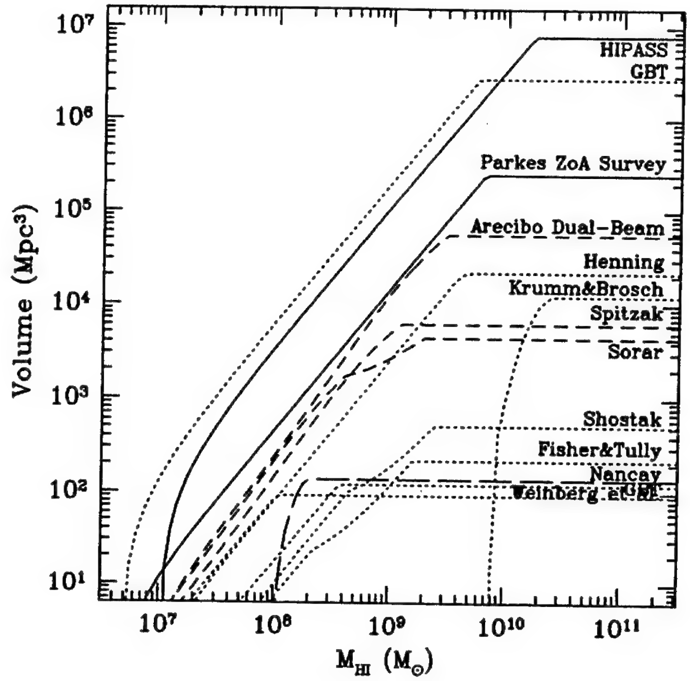

Fig. 4.— Volume sampled as a function of mass for various HI extragalactic surveys. A GBT multibeam survey would sample a volume similar to HIPASS at higher masses, filling in the census of HI-rich galaxies in the northern sky. It would also be significantly more sensitive to galaxies with HI masses less than $10^7\,M_\odot$.

6.2. Science Drivers

A multibeam system on GBT will provide many interesting possibilities for extragalactic investigation. We list a few of these major areas here:

- Determination of the HI mass function: While different surveys are starting to converge on a slope for the HI mass function, larger, deeper surveys will help define the significance of a low mass, HI-rich population of galaxies. All of the HI galaxies detected thus far appear to have an optical counterpart, but many are extremely low surface brightness optically. Will deeper surveys reveal HI galaxies without stars? The formulation of a sensitive HI mass function provides insight into the smallest object capable of retaining its neutral gas and the

hierarchical models of galaxy formation. Of equal importance are the indications that the HI galaxy populations vary as a function of environment. Is the gas being stripped away or collated within a cluster environment? Only with the larger samples accessible with a sensitive multibeam instrument can we begin a statistical study of the HI mass function with respect to environment.

- Extension of HI surveys down to lower column density: Sensitive maps of large scale HI structure may provide important clues into the origin of the lower HI column density Ly-alpha absorber systems and the distribution of baryons in the universe today. HI emission-line surveys are only sensitive to the highest column density gas in the universe, and we can only detect low column density gas in absorption along sightlines with a bright background source. The improved column density sensitivity of a multibeam system will allow regions to be searched for lower column density emission, for example near the Ly α absorbers. Previous work has examined the link between optically detected galaxies and the absorbers. A sensitive HI survey of large scale structure will allow an examination of the link between the absorbers and gaseous galaxies.

- Extension of HI surveys to higher redshift: With the sensitivity and bandwidth to access higher redshift objects, we will, for the first time, be able to investigate the nature of the densest gas over cosmologically important timescales. A higher accretion rate is predicted at higher redshifts by current galaxy formation models, with the cold gas providing the fuel for star formation. Higher redshift observations allow one to reach further towards the epoch of galaxy assembly.

6.3. A GBT Survey

A beam-forming array on the GBT would allow a large scale extragalactic HI survey to be completed with greatly improved resolution over previous all-sky surveys such as HIPASS. Such a survey would have much less of a problem with source confusion and the lower noise would give improved sensitivity to low mass sources. A survey covering the northern half of the sky at 5.8 mJy sensitivity with 20 km/s channel spacing would take 360 days. Figure 4 shows that this type of GBT multibeam survey would sample a volume similar to HIPASS at higher masses, filling in the census of HI-rich galaxies in the northern sky. It would also be significantly more sensitive to galaxies with HI masses less than $10^7\,M_\odot$.

At higher redshifts, individual regions can be studied deeply. To cover a 1 deg^2 area at $z = 0.1$ down to 10^8 M$_\odot$ it would take about 74 hours. It is therefore possible to start studying clusters at cosmological distances and examine the evolution of gas with redshift and environment.

The GBT could also be used to survey for redshifted OH masers; this could easily be accomplished by piggybacking on pulsar surveys.

7. Pulsar Surveys

7.1. Science Goals

The proposed beam-forming array on the GBT will provide a valuable complement to the current Parkes and forthcoming Arecibo multibeam pulsar surveys along the Galactic plane. With frequency channels at least a factor of 7 narrower than those at Parkes, a pulsar survey with the GBT will probe much greater distances for short period pulsars.

A search within 5° of the Galactic plane may be expected to find young pulsars, the recent products of supernova explosions. Young and middle-aged pulsars are the most prone to rotational glitches and timing noise, and new examples will greatly help statistical studies of these phenomena (Lyne, Shemar, & Graham-Smith 2000, Wang *et al.* 2000). The fields around the youngest pulsars can be searched for supernova remnants in followup imaging studies; this is underway for the Parkes multibeam pulsars (Crawford *et al.* 2001). The Parkes survey has also uncovered a new set of radio pulsars with extremely high surface magnetic fields: over 10^{13} G, approaching magnetar strength (Camilo *et al.* 2000). Future surveys that yield extreme examples will constrain the relative birth rates (branching ratios) of various kinds of neutron stars and their relationships to SNRs. Further constraints on emission and the possible radio "death line" will be obtained if the surveys are lucky enough to find very slow pulsars, such as the 8.5-second pulsar recently identified at Parkes (Young, Manchester, & Johnston 1999); note that such slow pulsars may also be radio relatives of the Anomalous X-ray Pulsar (AXP)-type magnetars.

The Parkes multibeam survey is proving enormously successful, with over 600 pulsars found at the 85% mark of the survey. This search has already nearly doubled the known population of pulsars, and will permit more thorough investigations of the birth distributions in period, magnetic field and luminosity. With longer-term timing, proper motions will be found for many of these pulsars. These measurements will provide much information on the range of velocities at birth (Lyne & Lorimer 1994, Cordes & Chernoff 1998) and hence on the properties of asymmetric kicks in supernovae. The collection of pulsars can also be used for studies of the interstellar medium, allowing better determinations of the dispersion measure–distance relation (Taylor & Cordes 1993), the ISM magnetic field from rotation measures (Han, Manchester, & Qiao 1999), and the structure and turbulence of the ISM from scintillation and scattering studies (e.g., Bhat, Gupta, & Rao 1999). Further large-scale surveys based at Green Bank and Arecibo will probe larger and deeper regions of the Galaxy and will vastly increase the scientific gain from these types of statistical studies.

All of these surveys may of course be expected to discover a certain number of binary pulsars. Searches targeting the Galactic plane specifically stand a very good chance of finding low-velocity, high-mass systems such as the pulsar with a mysterious 11 $M_{\odot}$ companion discovered in the Parkes survey (Stairs *et al.* 2001). This is therefore the ideal type of survey with which to pursue the predicted class of pulsar–black hole binaries (Bethe & Brown 1998). Other types of systems recently found in the plane include a double-NS system (Lyne *et al.* 2000), only the second young-pulsar–

white-dwarf system known (Kaspi *et al.* 2000), and several pulsar–white dwarf systems with mildly recycled neutron stars (Camilo *et al.* 2001). Clearly, the discovery of more of any of these types of systems, or of new types of binaries, will allow a more complete understanding of the populations of each, as well as the different possible branches of binary evolution. With the greater sensitivity of the GBT, shorter integration times will be needed to reach the same distance as the Parkes survey, meaning that there will be fewer selection effects operating against the discovery of fast, relativistic binary systems.

7.2. Selection Effects in Pulsar Surveys

Pulsars are steep-spectrum objects, with typical spectral indices around −1.6. For this reason, pulsar searches have historically been conducted at frequencies of a few hundred MHz. However, such surveys have difficulty seeing the bulk of the pulsar population in the Galactic plane due to a number of selection effects.

The data from each survey pointing must be searched in multiple unknowns: dispersion measure (DM), pulse period, and possibly acceleration. The search in DM is accomplished by dividing the observing bandpass into multiple narrow channels of width $\Delta\nu$, and dedispersing the data at a number of trial DMs, up to the expected galactic limit in the given direction. The periodicity search is then achieved by a Fourier Transform of each of dedispersed time series and involves summation of harmonics to increase sensitivity to pulsars with short duty cycles.

The highest sensitivity to (especially) fast pulsars will be retained when the dispersion smearing across a single channel is less than the (*a priori* unknown) pulse width. This DM broadening scales as $\nu^{-3}\,\Delta\nu$, where ν is the observing central frequency; it is therefore a much more serious effect at low frequencies, especially in the Galactic plane, where high DMs are expected. Another effect which broadens the pulse profiles is scattering due to multipath propagation in the ISM; this has the effect of convolving the pulse profile with an exponential tail. As the scattering timescale scales as $\nu^{-4.4}$, this effect can also be mitigated by observing at higher frequencies. A final propagation effect which can harm surveys is diffractive scintillation of the pulsar signal; however, for high-DM pulsars in the Galactic plane, the typical decorrelation bandwidths for such scintillation at 1.4 GHz should be considerably smaller than the large available total bandwidths, minimizing the problem. Scintillation will still be a problem for mid- or high-latitude searches, and multiple pointings in each search direction may be needed.

It is worth pointing out that the sampling rates anticipated for a GBT beam-forming array survey ($\sim 50\mu$s) is much faster than that of the ongoing Parkes Multibeam survey (250μs), making the proposed GBT surveys far more sensitive to millisecond pulsars than the Parkes survey. While the Lovell Telescope at Jodrell Bank, U.K., can see much of the same part of the sky as the GBT, and is indeed planning a pulsar multibeam survey, the larger gain and bandwidth and smaller

channels planned for the GBT survey mean that the GBT will discover more pulsars than Jodrell Bank in significantly less time.

The overall limiting sensitivity of a survey is a function of the telescope gain, the receiver temperature and the sky background temperature. The background temperature is again high along the Galactic plane, but is also a strongly decreasing function of frequency, making 1.4 GHz a good choice. In order to achieve a good sensitivity, therefore, it will be crucial to cool the multibeam receiver as well as possible; the proposed target of 25 K will be acceptable.

Other problems that may affect the success of a survey include the Doppler smearing of signals from fast-orbiting pulsars, and swamping of pulsar signals by interference. The low-rfi environment at Green Bank means that the interference situation will be quite good to begin with; in particular, the types of long-period rfi that make it difficult to find long-period pulsars should be greatly reduced compared to other sites. The Parkes survey team has developed routines which cross-correlate the signals from the different beams and thereby identify interference; such techniques could also be applied to Green Bank multibeam data if needed. The Doppler shifting of accelerated pulsars may not be a serious problem if the integration times are short (see §7.4 below); but depending on computer resources it may be worthwhile to perform incoherent or even coherent acceleration searches on the data. The data processing requirements will be large, but search processing will be divided among the institutions participating in the surveys.

7.3. Why the GBT Should be Used for Deep Pulsar Surveys: 10 Reasons

1. The Radio Quiet Zone should be exploited.
2. The GBT can be used efficiently by dynamically scheduling pulsar surveys when weather conditions prohibit other observations.
3. The GBT and associated fast dump spectrometers can search much more deeply than other telescopes (in directions inaccessible to Arecibo).
4. A large sample of new pulsars will complement those found with the Parkes multibeam survey in the Southern hemisphere and with an anticipated multibeam survey with Arecibo.
5. Large pulsar samples allow detailed modeling of the Galactic electron density and its fluctuations and the Galactic magnetic field.
6. Significant numbers of (or limits on) extreme or outlier objects will be found: sub-ms pulsars, NS-NS binaries with orbital periods smaller than a few hours, perhaps a NS-BH binary, pulsars with other orbital companions (WD, main sequence stars, planets), and pulsars with very high magnetic fields ($> 10^{13}$ G).

7. Extreme objects allow probing of fundamental physics (GR, the equation of state of nuclear matter) and exploration of the astrophysics of NS formation (R-modes and gravitational wave-driven spindown, spin driven generation of magnetic fields).

8. A large sample allows the pulsar birth rate to be better estimated; signatures of variation in BR both spatially (e.g. in spiral arms) and temporally (star bursts) can be sought.

9. NS-SNR associations can be established with robust statistics, particularly given that ongoing or imminent VLA and XMM surveys will identify SNRs over almost the entire Galaxy.

10. The merger rates of binaries (NS-NS, NS-WD and NS-BH) can be estimated with much better precision; these rates are relevant to LIGO and GRB models.

7.4. Proposed Searches with the GBT

We have carried out simulations assuming: T_{sys} 25 K, gain 2.0 K/Jy, BW 200 MHz, $\Delta\nu$ 200/512 MHz, sampling rate 50 μs, 7 beams, each $9'$. A simulated search with 300 s per pointing in the galactic latitude range ± 5 degrees for zenith angles < 70 deg is shown in Figure 5. The number of simulated detections is 512. The assumed parameters of the pulsar population are based on those in Arzoumanian, Chernoff & Cordes (2001) and related papers; a distribution of pulsars is simulated and subjected to detection methods and selection effects expected in the survey. The simulated pulsars are assumed to be born preferentially in the spiral arms of the Galaxy, with a kick velocity, and to move in a Galactic potential that includes Galactic rotation. Kick velocities, braking indices and luminosities reflect those of the known pulsar population.

Table 1: Predicted numbers of young pulsars:

T_{int} (s)	T_{survey} (hr)	Number of Pulsars
600	3400	782
300	1700	512
180	1000	417

Millisecond pulsars: Using the Parkes multibeam system, Edwards and Bailes (2001) found 8 MSPs in $\sim$ 336 hr, i.e. a rate of 42 hr/MSP. For equal integration times using the Parkes multibeam system (13 beams with FWHM $= 14'$) and the GBT (7 beams of $9'$), Parkes searches solid angles at a rate of 4.5 times that of the GBT. However, with its greater gain and using 200 MHz for the GBT compared to 288 MHz for Parkes, the GBT searches to a distance (D_{max}) that is 2.8 times further. The net *volume* coverage is therefore about 1.6 times greater per hour for the Parkes multibeam system. By cutting the search time per pointing to 2 minutes, compared to 4 minutes, the volume

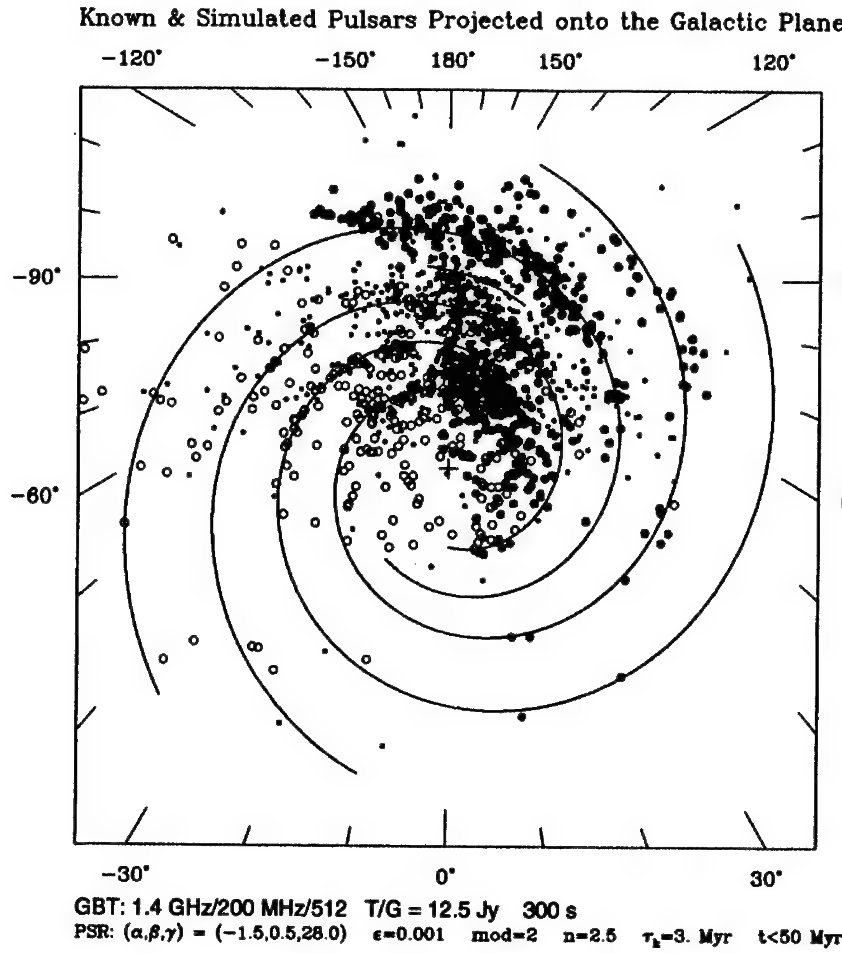

Fig. 5.— Simulated pulsar detections from a GBT multibeam survey with 300 s per pointing in the galactic latitude range ±5 degrees for zenith angles $< 70°$. Black dots are known pulsars in the Princeton pulsar catalog. Open black circles are the public subset of pulsars from the Parkes Multibeam Survey. Green circles are simulated detections with a GBT system.

rate would be larger for the GBT. The advantage to the GBT is larger than this, however, because channel bandwidths will be smaller than with the Parkes system. In summary, using the nominal gain, 7 beams, 512 channels across 200 MHz, and 2 minute integrations in a search at moderate latitudes (e.g. $5 \leq |b| \leq 15$ deg) we expect to find MSPs at a rate of roughly 1 per 30 to 40 hr of telescope time.

8. Continuum Observing

The GBT's main contributions for L-band continuum observing will be in mapping extended sources and searching for radio transients. The primary advantages of the beam-forming array for

these projects will be in the "speed-up" factor and the data quality monitoring that it will provide.

The brightness sensitivity of the filled-aperture GBT is much greater than that of the VLA, meaning that the GBT will complement VLA imaging of extended sources. Large, diffuse Galactic sources, like the North Polar Spur, are difficult or impossible to map with the VLA; moderately extended sources (up to about 3°, e.g., M31, the California Nebula, the Cygnus Loop) can be imaged, but at the cost of resolving out the most diffuse portions of the sources. In the latter case, the GBT observations will provide short-spacing data to supplement VLA observations.

The radio sky is poorly surveyed for transient sources. Surveys at other wavelengths, particularly X- and gamma-ray, have been quite successful at detecting new classes of sources and suggest that the radio sky may contain additional classes of highly variable or transient sources. The sensitivity of the GBT will be limited strongly by confusion (≈ 20 mJy beam^{-1} even at high Galactic latitudes). Because the confusion limit is composed (presumably largely) by constant intensity sources, transient sources somewhat below the confusion limit can be detected by differencing observations from two epochs. The small beamwidth means that surveying large regions of the sky will be possibly prohibitively time consuming. Nonetheless, selected regions of the sky (e.g., portions of the Galactic plane or M31) might be targeted usefully, similar to the Galactic Plane survey A being conducted currently with the NRAO-NASA Earth Station instrument (Langston *et al.* 2000).

Multibeam scans make it much easier for the observer to recognize and excise data corrupted by interference, bad weather, and receiver baseline drifts or other glitches. This data quality monitoring capability will be particularly useful for discriminating real celestial transients from terrestrial interference (e.g., requiring that celestial transients be seen in only one beam).

The proposed bfarray sensitivity specifications (25 K system noise, 100 MHz bandwidth) are more than adequate for the proposed continuum observing projects. The main concerns for continuum work are

1. Receiver gain fluctuations should be less than 1 part in 10,000 on time scales of seconds (the time needed to scan across a source extended by a few degrees) and less than 1 part in 1000 on time scales of a few minutes (the time needed to scan across the largest Galactic structures);

2. Spillover baseline variations with elevation should be small for mapping the largest structures; and

3. The strongest sidelobes (e.g., the residual coma lobe) should be below −20 dB for accurate imaging.

9. Summary of Requirements

Table 2: Required parameters for different types of observations

Parameter	HI line and pol	Continuum pol	OH	Continuum	Pulsar
Gain fluctuation				$< 10^{-4}$, seconds $< 10^{-3}$, minutes	
Spillover variation with elevation				"small"	
Strongest sidelobes		Q, U: $< 15\,$dB		$< 20\,$dB	
Center frequency (MHz)	≤ 1420	1420	1612, 1665, 1667, 1720	Any, 5 GHz	Any, possibly higher
Bandwidth (MHz)	5	100	0.8	100+	200+
Velocity resolution (km/s)	0.6		0.5		
Spectral resolution (kHz)	3	1562.5	3		≤ 400
Sample rate (μs)					≤ 50
Bits saved					2,4,8
Data rate (200 MHz, 1 beam)					5 MB/s
Data rate (200 MHz, 7 beams)					36 MB/s

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